

Levelling Machine and Method

The present invention relates to a levelling machine and to a method of operating and calibrating a levelling machine.

Levelling machines for working the coiling tendencies out of hot or cold rolled wound strip, and sheet or plate metal are well known. Levellers remove flatness anomalies from metal strip by longitudinally deforming it by deflection over a series of parallel rollers by successively smaller amounts from the entry to the exit of the machine and by differing amounts laterally across its width. A line of upper and lower work rolls are positioned offset to each other to effectively bend (deform) the strip back and forth until the coiling tendencies are removed from the workpiece, and the piece is flat with equalised internal stresses and more useful for further manufacturing processes. Such machines are also used to remove edge and/or centre waves from strip, sheet or plate and other lateral defects.

Typically, roller levellers comprise a main housing supporting a cassette portion(s) housing upper and/or lower work rolls. Often such machines have a raisable upper work roll group and a lower work roll group; for example; the upper work rolls and associated backup rollers may be mounted within an upper housing that can be adjustably moved up or down in relation to a housing by means of screw threads. Alternatively, the upper work roll group may be fixed and the lower work roll group may be raisable. Adjustment means such as hydraulics may also be used. Traditionally, such machines have required constant adjustment by highly skilled operators in order to produce an acceptably flat product. The latest levelling machines provide a degree of automatic control by allowing an operator to program the machine to remove a certain type of strip fault; for example edge wave, by setting and maintaining a fixed gap between the top and bottom rollers. However, as the type and degree of fault correction required usually varies continuously as a coil of sheet material is unwound such partial automation has significant limitations.

An aim of the present invention is to provide an improved levelling machine that is easier to set up and to operate and in particular a machine that automatically responds to changing

faults in strip as it is unwound. Another aim is to provide a levelling machine that is capable of performing automatic self calibration. A further aim is to provide a method of automatically adjusting a levelling machine to respond to various and changing faults in incoming strip material.

In one aspect the invention provides a levelling machine comprising upper and lower work rolls for engaging a workpiece; upper and lower backup rollers supporting the work rolls against the workpiece; upper and lower backup carriers to which the upper and lower backup rollers are rotationally mounted respectively; a first pivot axis about which the lower backup carriers may pivot; a second pivot axis about which the upper backup carriers may pivot; wherein the first and second axes are substantially parallel and in use are fixed in position one relative to the other.

The upper rolls may comprise a series of rollers mounted on bearings where the axes of rotation of the bearings lie on a common plane. Similarly, the lower rolls may also comprise a series of rollers mounted on bearings where the axes of rotation of the bearings lie on a common plane. Preferably, intermediate rolls are located between the upper work rolls and the upper backup rollers. This stiffens the upper work rolls and so largely prevents bowing of these rolls as the workpiece is processed. Preferably, the first pivot axis is coincident with axis of rotation of last roll of lower work rolls and the second pivot axis is coincident with axis of rotation of first roller of upper work rolls; this provides the ideal pivot configuration in cases where the upper and lower work rolls each have axes lying on common planes. Preferably, the number of upper work rolls will be one more or one less than the number of lower work rolls. Preferably, there are between 5 and 13 lower work rolls; and most preferably 9. Preferably, the number of rows of upper backup rollers will be one more or one less than the number of rows of lower backup rollers. Preferably there are between 4 and 12 rows of lower backup rollers; and most preferably 7. Normally, all of the work rolls will have the same diameter, D and will be displaced at equal work centres C ; in which case the second pivot axis may be a vertical distance D above first pivot axis and horizontal distance $C(0.5N-1)$ from first pivot axis; where N is the total number of work rolls.

The lower backup carriers are preferably mounted at equally spaced intervals across the width of the lower work rolls; normally within a lower cassette. Likewise upper backup carriers are preferably mounted at equally spaced intervals across the width of the upper work rolls, normally within an upper cassette.

In another aspect the invention comprises a levelling machine comprising an upper set of work rolls with a set of backup rollers, wherein the backup rollers are rotationally mounted within an upper backup carrier pivotable about a first axis; and a lower set of work rolls with a plurality of sets of backup rollers each in a carrier, wherein each carrier is pivotable about a second axis; and where the first and second axes are substantially parallel.

In a further aspect the invention comprises a method of levelling strip metal using a strip metal leveller according to any preceding claim comprising the steps of: measuring the reaction load at the pivot axes of individual lower and upper backup rollers; measuring the vertical displacement of the upper backup roller carriers and the individual vertical displacement of the lower backup carriers; and adjusting upward forces applied proximal the free end of each lower backup roller carrier to induce calculated reaction loads; wherein said calculated reaction loads are calculated by an algorithm based upon there being a uniformly distributed stress across the material being processed as it exits the work rolls.

Preferably, intermediate rolls are provided between the upper work rolls and the upper backup rollers. The position of the second pivot axis and/or the upper backup carrier relative to the first pivot axis is in use fixed. This provides means of adjusting the machine to process sheet metal of varying thickness and yield strength. An algorithm is used to calculate the required upward forces applied near the free ends (load points) of individual lower backup carriers preferably includes equations that describe a continuous beam when subjected to a uniformly distributed load whilst being supported in a manner as prescribed by the configuration of the intermediate and backup rollers. The upward forces may be applied to the

backup carriers by hydraulic means. Load cells may be used to measure the reaction load at the load points. The vertical displacement of the upper and lower backup carriers may be measured using linear transducers, one for top backup carrier, and one for each of the bottom backup carriers.

Thus, in use, the upper and lower pivot axes are fixed in position relative to each other; for example by attachment to a common frame; load cells are provided at the load points to continuously measure loads (L) induced into the material by the machine during levelling or processing; variable forces (F) are applied at or near to the free ends of each lower backup carrier; preferably by fast acting hydraulic means; and position detectors are provided to monitor vertical displacement (X) of individual lower backup carriers. Preferably, an algorithm calculates in real time the values of F from measured values of L required to ensure a uniformly distributed load laterally across the material being processed as it exits the work rolls.

In a further aspect the invention comprises a method of levelling material using a levelling machine comprising upper work rolls and lower work rolls said lower work rolls being supported by a plurality of lower backup rollers, means of measuring the reaction load at support point for each backup roller and a Load Control Algorithm for controlling the process comprising the following steps: calculating the expected distribution of load at said support points assuming the lower work rolls to be slender beams carrying a uniformly distributed load over the contact area of the material and supported by the lower backup rollers; calculating the differences between said expected load distribution and a measured load distribution (XLO); adjusting machine parameters until said calculated difference (XLO) is near to or equal to zero.

A preferred embodiment of the invention will be described by reference to the following diagrammatic figures in which:

Figures 1 and 2 illustrate the geometry of the rollers in a machine according to the present invention;

Figure 3 shows a side view of a levelling machine according to the invention;

Figure 4 shows a front view corresponding to Figure 3;

Figure 5 shows a side view of the main frame and cassette components of the levelling machine shown in Figure 3;

Figure 6 shows a front view corresponding to Figure 5;

Figures 7 and 8 show a plan view and an underside view respectively of selected components of the cassette of the machine of Figure 3;

Figure 9 shows a side view of the roller assemblies within the upper and lower cassettes for the machine of Figure 3 in more detail;

Figure 10 is a front view corresponding to Figure 9;

Figures 11 and 12 show the control arrangement for the machine of Figure 3; and

Figure 13 shows a the cassette removal system in both a retracted and withdrawn position.

The geometry of the upper and lower roll sets will be described by reference to Figures 1, 2, 7 and 8. In this example there are nine lower work rolls ($R_1, R_3 \dots R_{17}$) of equal diameter D arranged side by side, but not quite in contact with each other; the axes of rotation of these lower work rolls falling on a common plane $A-A'$. The lower work rolls are supported by four sets of eight backup rollers and three sets of nine backup rollers rotationally mounted in a staggered manner within seven lower backup carriers (see Figure 8); these lower backup carriers can pivot about an axis P_1 ; this axis being coincident with the rotational axis of the last lower work roll R_{17} . Likewise there are eight side by side upper work rolls ($R_2 \dots R_{16}$) of equal diameter D , the axes of rotation of these rolls falling on a common plane $B-B'$. Thus, an upper roller assembly comprises eight upper work rolls, nine staggered intermediate rolls of slightly smaller diameter, four sets of eight backup rollers and four sets of nine backup rollers mounted in a staggered manner on both sides of an upper support carrier (see Figure 7). The upper backup rollers can also each pivot about an axis P_2 ; this axis being coincident

with the rotational axis of the first upper work roll R_1 . Figure 2 shows the lower roller assembly pivoted downwardly about pivot axis P_1 , in an exaggerated manner for illustration purposes

The work rolls are arranged in two rows; the first above, and the second below the material being processed, with their axis of rotation perpendicular to the direction of material flow in the horizontal plane. The work rolls have a common working face length that is greater than the width of material being processed. The work rolls are displaced at equal centres (C) from the entry to the exit of the machine in the horizontal plane. The first upper work roll (R_2 - see Figure 1) below which the material enters the machine is located above and equidistant between the first (R_1) and second (R_3) lower rolls. R_2 is fixed in position relative to the last lower roll R_{17} in both the vertical and horizontal planes. R_{17} is fixed in position a distance D_1 below R_2 , in the vertical plane and a distance equal to $C[0.5N-1]$ in the horizontal plane; where N is the total number of work rolls. The upper work rolls are separated from the upper backup rollers by a second set of equal face length intermediate rolls with a common diameter (d). The backup rollers and the intermediate rolls are not driven. The backup rollers are arranged in two different widths, with a greater number of narrower rollers at the entry to the machine and a lesser number of wider rollers at the exit of the machine.

Figures 3 and 4 show a levelling machine 10 with separate upper and lower work roll drive, motors 12 and 14 supported by a stand 16 or alternatively a single motor with a pinion stand to drive upper and lower work rolls. Machine main frame 18 houses all of the principal components of the machine apart from motors 12,14, and tracked beam 32. Main Frame 18 has centrally located front and rear openings 34,36 through which a work piece travels as it is levelled by its passage between the upper and lower work rolls 58 and 60. The main frame 18 also has side openings 20 that allow access to a roller cassette 22 housing the roller mechanisms.

Cassette 22 comprises lower and upper portions 24 and 26 respectively. Upper roll gear box 28 and a lower roll gear box 30 are fixed at a first end of the upper and lower cassette

portions respectively, and are an integral part of the cassettes; these gear boxes also couple the drive shaft of motors 12,14 to the working roll sets. The cassette is normally largely enclosed within the main frame 18 such that the gear boxes 28 and 30 engage drive shafts of motors 12 and 14 respectively or alternatively the output shafts of the pinion stand. This allows the upper work rolls to be driven by motor 12 via upper gearbox 28 and the lower work rolls to be driven by motor 14; the upper and lower work rolls are driven in synchrony. Alternatively, motors 12 and 14 may be replaced by a single motor that synchronously drives two shafts; these shafts engaging gear boxes 28 and 30.

Cassette 22 may be conveniently withdrawn from the main frame 18 by sliding it along tracked beam 32 that extends from the side of the housing opposite motors 12 and 14. Guide rails and associated track beam 32 support the cassette as it is withdrawn from the machine. During normal operation the cassette 22 is located within the main frame 18 and does not extend from it.

Figure 13 shows a preferred embodiment of a cassette removal system that may form part of the levelling machine of the present invention and that also may be used with conventional levelling machines that have a roller cassette. During levelling, the upper portion 24 of cassette 22 is positively clamped into a precise location within the main frame 18 of the machine by means of four upper clamps (not shown) each clamp being moveable vertically by means of a screw jack 300; one screw jack being located near each side corner of main frame 18. Movement of each screw jack 300 is synchronised and downward movement of the jacks and clamps results in the upper cassette being released from main frame 18 and lowered so that it rests on lower portion 26 of the cassette. This means that upper portion 24 of cassette 22 is removed at the same time as the lower portion 26 of cassette 22.

During levelling lower portion 26 of cassette 22 is similarly positively clamped into a precise location within the main frame 18 of the machine by means of four lower clamps (not shown) each clamp being moveable vertically by means of a screw jack 302; one screw jack being located near each side corner of main frame 18. Movement of each screw jack 302 is

synchronised and upward movement of the jacks and clamps results in the lower portion 26 of cassette 22 being released from main frame 18.

The cassette 22 or lower cassette portion 26 are removed from the main frame 18 by means of a support assembly 304 mounted on linear rollers (not shown) so that it may be moved horizontally by hydraulic means (not shown). Support assembly 304 comprises a generally rectangular shaped frame made up by an end plate 308 being fixed to a pair of arm members 310. The arm members 310 are mounted via rollers to the four lower clamps (not shown) and during the removal process these rollers are raised vertically as the lower screw jacks 302 are moved vertically upwards. This results in the support assembly 304 being lifted slightly and moving into contact with the cassette 22 or lower cassette portion 26 and thereby supporting it. The arm members 310 are preferably positioned parallel to and outside of the front and rear face of the main frame.

During removal of the lower portion 26 of the cassette lower screw jacks 302 move vertically upward, unclamp the lower cassette and raise the support assembly 304 so that it supports the cassette. Hydraulic means then push the cassette and support assembly 304 in a horizontal plane until the cassette is free of the main frame and can if required be lifted by an external crane or the like. Replacement of a cassette is achieved simply by revising the above steps.

Thus, the cassette can be removed from the main frame 18 using a completely self-contained removal mechanism; in contrast to known prior systems that rely on a structure external to the machine to support the cassette and/or a rail system in the floor adjacent to the machine.

Figures 5 to 8 illustrate the arrangement of the machine rollers. There are eight upper work rolls 58 arranged side by side, but not quite in contact with each other and nine lower work rolls 60 likewise arranged; the upper work rolls being the same diameter as the lower work rolls. The work rolls 58 and 60 rotate about roller thrust bearings located in upper and lower roll end chocks 64,66 located at each side of the upper and lower cassette portion 24, 26

respectively. The lower work rolls 60 are supported by sets of lower backup rollers 70, 72 and 74 arranged as a group and rotationally mounted within a lower backup carrier 68 (see Figure 6). There are seven such groups of lower backup roller each with its own carrier 68 and these groups are evenly spaced across the lateral workpath (the direction of material flow in the horizontal plane). Each of these backup carriers 68 may individually pivot about a common axis P_1 within lower cassette portion 24 under the influence of fast acting hydraulic cylinders (RAM). Axis P_1 is coincident with the rotational axis of the last lower work roll 60.

The lower backup roller groups each comprise a lead roller 70, followed by several staggered lower rollers 72 and finally an exit roller 74. Exit rollers 74 may advantageously be approximately twice the width of the lead and/or staggered rollers 70 and 72. (see Figure 8). As each of the lower backup carriers 68 (see Figure 6) may individually pivot about axis P_1 the last lower work roll (R_{17}) is always substantially supported by the lower exit roller 74 (see Figure 5). This allows fewer bearing elements and a long body roller to be used as the loads being supported are reduced. The upper work rolls 58 are supported by a set of upper backup rollers 92, 94 and 96 arranged as a group and rotationally mounted within an upper backup carrier 90 (see Figure 6). There are eight such sets of upper backup rollers each with their own backup carrier 90 and these groups are evenly spaced across the lateral workpath. The upper backup carriers 90 are staggered with respect to the lower backup carriers 68. The upper backup carriers may pivot in unison about a common axis within upper cassette portion 26 (about an axis P_2) under the influence of a roll pivot actuator 100 (see latter). Axis P_2 is coincident with the rotational axis of the first upper work roll (R_2). Within the upper cassette portion 26 intermediate rolls 62 are provided between the upper work rolls 58 and the sets of upper backup rollers. Upper work rolls 58 are staggered between the intermediate rolls 62 which are of slightly smaller diameter than the work rolls 58,60. The intermediate rolls 62 are mounted between thrust bearings within the upper cassette portion 26 so that they may rotate about axes substantially parallel to the rotational axes of the upper work rolls 58 and the upper backup rollers.

Vertical movement of the upper work rolls 58 is restrained by the intermediate rolls 62 and the eight sets of upper backup rollers (each in carrier 90) spaced evenly across the width of

the upper work rolls 58. The lower work rolls 60 are likewise restrained from free vertical downward movement by the 7 sets of lower backup rollers (each in carrier 68) evenly spaced across the width of the lower work rolls 60. The upper work rolls 58, lower work rolls 60, intermediate rolls 62, upper and lower backup roller sets (and backup carriers 68 and 90) and gearbox assemblies 28, 30 are all housed within the upper and lower portions of cassette 22 and assist the placement and removal of these components from the main frame of the machine 18.

Figures 9 and 10 show the cassette 22 in more detail and also how it is housed within the main frame 18 and how the upper and lower work rolls operably pivot about axes P_1 and P_2 . The seven lower backup carriers 68 may all independently pivot about a first pivot axis P_1 (see Figure 1); the pivot axis P_1 (see Figure 9) being provided by bearings (105) located in the main plate of the lower cassette portion 24. The eight upper backup carriers 90 may pivot in unison about a second pivot axis P_2 (see Figure 1); the pivot axis P_2 (see Figure 9) being provided by bearings (106) located in the main plate of the upper cassette portion 26. Thus, the lower and upper backup carriers sets are both pivotably mounted to a cassette 22 normally fixed within main frame 18. The position of pivoting axis P_2 (104) is fixed relative to axis P_1 .

Loads are measured by load cells comprising strain gauges (not shown) located at each of seven lower and eight upper load points. These load points are located at a point on the pivot axes of each upper and lower backup roller 68, 90 (see Figure 6). Although each of the upper backup roller carriers 90 pivot in unison; this does not mean that in use the load is evenly distributed at each load point; hence it is necessary to measure the load at each upper load point as well as at all the lower load points. Thus, eight upper load cells 98 are fixed to main frame 18 and are located in vertical alignment with the eight upper load points. Seven lower load cells 76 are also fixed to main frame 18 and are located in vertical alignment with the seven individual lower load points; one for each independently pivotable lower backup carrier 68. Each load cell uses twelve strain gauges in a full bridge configuration to measure resistive changes in the gauges that are proportional to the amount of strain induced. Electronic components embedded within each load cell convert the measured change in resistance into a digital signal. The load cells are synchronised by an external signal so that they measure and

transmit data simultaneously. The load cells incorporate facilities for automatic temperature compensation and zero and span calibration.

Variable loads may be applied to the material by individually pivoting each lower backup carrier 68 about its pivot axis P_1 by using fast acting hydraulic cylinders 78 (RAMs); load is increased by clockwise movement about the pivot axis and decreased by anti clockwise movement. The angular position of the upper backup carriers about their common pivot axis P_2 is adjusted by means of roll pivot actuator 100; this may incorporate a cam, eccentric shaft, sliding wedge arrangement, or the like (see Figure 9); rotation of the cam or the like resulting in movement of the actuator vertically, and hence pivoting of the upper backup carriers in unison about point P_2 . The rate of change of loading along the workpath resulting from the pivoting of each row of the lower backup carriers 68 is determined by the angular position of the upper backup carriers; and this rate change increases as the angular displacement of the upper backup carriers 90 increases in a clockwise direction.

Figures 11 and 12 show details of the control system of the levelling machine. The top roll set has an entry load cell at each upper load point 200 to 207 and one adjustment device 216, which rotates all top backup carriers collectively about their pivot axis (P_2). A single position feed back device, 218 is included to transmit the position of the top roll set to the Real Time Controller (RTC) 220 and the Human Machine Interface (HMI) 222. The bottom roll set has an exit load cell at each lower load point, 208-214 and hydraulic RAMs 231-237 near the free end of each lower backup carrier 68. Each RAM 231-237 has an associated position feed back device 238-244 to transmit the position of each bottom backup carrier 68 to the RTC 220 and the HMI 222. Each of the RAMs, 231 to 237 has a valve attached to it to control the pressure in the RAM and hence the force applied to the material via individual lower backup carriers 68 and their associated rollers. Each of the pressure control valves is connected to the RTC 220 so that the force applied can be set by the RTC. The entry and exit load cells 98 and 76 respectively are connected to the RTC via fifteen individual data buses and two common command buses. The RTC 220 receives data from the HMI 222 relative to the parameters of the material being levelled. These parameters include width, thickness and yield strength. The RTC 220 uses data from the HMI 222 together with a Load Control Algorithm (LCA) to

constantly adjust the pressure control valves (and hence the force applied to each hydraulic RAM 231 to 237). All pressure control valves, position feed back devices, top roll set positioning device and top and bottom roll drives are connected to a controller area network (LAN) to which the RTC 220 and HMI 222 are also connected. The HMI acts as the entry point for all operator inputs and the display point for all relevant process data and diagnostic information.

Upper work rolls 58 are substantially more rigidly supported and thus less compliant than the lower work rolls 60 due to the greater number of rows of upper backup rollers 92, 94 and 96 than lower backup rollers (see Figure 6) and the addition of intermediate rolls 62 (see Figure 5). During the levelling process the material is subjected to greater deformation by the entry side work rolls R_1 , R_2 , R_3 etc. (see Figure 1) and lesser deformation by the exit side work rolls R_{15} , R_{16} , R_{17} etc. The amount of deformation of the material is proportional to the load imparted upon the work rolls; therefore the load imparted upon the upper (entry) load points 98 is substantially greater than that imparted upon the lower (exit) load points 76. On entry to the work rolls, the resistance to deformation of the material across its width is unknown as it may contain out of flatness anomalies. The material being levelled is considered to apply a load to each work roll over its contact area with such load reducing and becoming uniform as the material is deformed by its passage between the work rolls the material becoming level as it exits them.

A Load Control Algorithm (LCA) calculates the expected distribution of load at the lower (exit) load points 76 when considering the lower work rolls 60 as slender beams carrying a uniformly distributed load over the contact area of the material and supported by the lower backup rollers 70, 72 & 74 (see Figure 8). The LCA calculates the differences between the measured and expected load distribution at the lower (exit) load points 76; these differences being the Exit Load Offsets (XLO). The overall purpose of the LCA is to achieve real time XLO values as close to zero as possible by adjusting machine parameters. Thus, the distribution of loads measured at lower load cells 208-214 is set to be, as near as possible, equal to the theoretical distribution calculated from the above mentioned ideal beam loading calculation.

Depending upon the material thickness and yield stress the LCA calculates an initial amount of deformation to be applied on entry to the work rolls. The amount of deformation applied is that which is calculated to cause a sufficient amount of the material cross section to be stressed beyond its elastic limit and so become substantially uniformly plastically deformed.

The LCA uses input data from the upper load cells 200-207 and lower load cells 208-214 (see Figures 11 and 12), upper position transducer 218 and lower position transducers 238-244 (see Figure 11) together with the material parameters width, modulus of elasticity, thickness and yield stress. The calculations performed by the LCA are based on the distribution of load across the eight upper (entry) load points 98 and the seven lower (exit) load points 76. Preferably, the LCA also calculates the expected distribution of load at the upper (entry) load points 98 assuming the upper work rolls 58 to be slender beams carrying a uniformly distributed load over the contact area of the material and supported by the intermediate rolls 62 and upper backup rollers 92, 94 & 96 (see Figure 7). The LCA then calculates the differences between the measured and expected load distribution at the upper (entry) load points 98; these differences being the Entry Load Offsets (ELO). The instantaneous force required to be exerted by each of the seven RAM's 231-237 in order to obtain near zero values of XLO may then be calculated from the ELO and other input data mentioned above. The ELO may be attributable to the out of flatness anomalies of the material at various points across its width as it enters the work rolls.

In operation, a Real Time Controller (RTC) controls the application of instantaneous loads to each of the lower backup carriers 68. The RTC executes the LCA at the necessary rate to produce flat material at various operating speeds up to the maximum operating speed of the levelling machine. Thus, the LCA continually calculates the precise loads to be applied by the RAMs 231 to 237 (see Figures 11 and 12) to each lower backup carrier 68 so as to obtain a distribution of reaction loads at the lower (exit) load points 76 (see Figure 9) that is substantially equal to the distribution calculated assuming that the exit work rolls of the

machine carry a uniformly distributed load over the area of contact of the material being levelled.

The mechanical properties of the material being processed may also be verified using the apparatus of the invention. Thus, the LCA may calculate the load expected to be imparted at the upper and lower load points 76, 98 by the levelling process from the material parameters width, modulus of elasticity thickness and assumed yield stress, together with the position of the upper work rolls as indicated by position transducer 218 (see Figure 11) and the lower work rolls as indicated by position transducer 234. The assumed yield stress may then be iteratively varied until the calculated and measured loads at the upper 98 and lower load points 76 are equal; thereby allowing the actual yield stress of the material to be measured.

The control system will be programmed so that an automatic machine calibration (AMC) procedure of the levelling machine can be carried out. The AMC procedure will set RAM upper stroke limits and parallelism offsets from datum RAM 234 and set top roll maximum clockwise rotation limits. The control system will be programmed so that a material calibration procedure, (MCP) can be carried out to calculate the yield strength of the material. The MCP will determine the yield strength of the material by measuring the force necessary to deflect the material between the top and bottom work rolls a predetermined amount.

While the embodiment described above has nine lower work rolls, the number of such rolls may vary; for example, according to the length of the workpath. The number of upper work rolls is preferably one more or one less than the number of lower work rolls. While it is preferable to have intermediate rolls, this is not essential. The diameter d of the intermediate rolls is preferably approximately equal to the diameter D of the upper and/or lower work rolls. While it is preferable for all of the lower backup carriers to pivot independently, this is not essential; for example two or more lower backup carriers may pivot in unison. While it is preferable for the upper backup carriers to pivot in unison, this is not essential; for example, two or more may pivot independently.